Plate Tectonics, Seafloor Spreading, and Continental Drift: an Introduction[1]

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Abstract The present ruling theory of geotectonics—commonly known as the "new global tectonics"—includes the concepts of plate tectonics, seafloor spreading, continental drift, and polar wandering. Recent seismic activity defines the positions and relative movements of rigid lithosphere plates. The geomagnetic time scale for polarity reversals seems to be calibrated to about 4 m.y. ago, and extrapolated to about 80 m.y. ago by correlation of oceanic magnetic anomalies with reversals and seafloor spreading. Seafloor spreading and the magnetic anomalies thus indicate the directions and rates of movements of lithosphere plates during the last 80 m.y. The continents drift with the lithosphere plates, and independent paleomagnetic evidence permits location of the relative positions of the continents and the poles to 500 m.y. ago, or more. The theory, which explains phenomena previously unexplainable, is supported by a mass of persuasive evidence. There is no doubt that the theory is a success, but it has been so successful that it has become a ruling theory, and subservience to a ruling theory never has served science well. There are data which do not seem to fit the theory. We should strive to keep open minds and to search for alternate solutions to fit all of the data. The record is clear: today's history was yesterday's model. Dare we conclude that at last we know the answers?

Introduction

Theories come and go, but during the last 12 years one theory has come along very rapidly—so rapidly, in fact, that we now are in the position of having a single ruling theory—the new global tectonics (Hess, 1960, 1962; Dietz, 1961; Morgan, 1968; Heirtzler *et al.*, 1968; Isacks *et al.*, 1968). The global scheme is illustrated schematically in Figure 1. Unfortunately, there is no competing theory. Thus, we are far from the method of multiple working hypotheses—the method which we geologists (in fact, *all* scientists) are supposed to follow (Chamberlin, 1890). I do not mean to imply that it is time to discard the new global tectonics—far from it. A large body of data has been gathered from the ocean basins and from studies of paleomagnetism to demonstrate that the new global tectonics may indeed be what Hollis Hedberg in 1970 called "the answer to a maiden's prayer." However, it *is* time for geologists to reflect and consider the evidence for and against this ruling theory, rather than to assume that the final word has been handed down.

This review presents a brief introduction to the theory, providing a background for the following articles, which deal in detail with specific topics. It is based on a tape recording of an unscripted and over-illustrated talk, and many illustrations discussed have not been reproduced here. The tape was transcribed and edited by A. A. Meyerhoff, and I thank him for converting my spoken words with an English accent into grammatical American prose.

No attempt was made to compile a complete bibliography. Those interested in more detailed reviews and bibliographies can find them in books by Drake (1970), Maxwell (1970). and Wyllie (1971a, b) and in several of the U.S. Quadrennial Reports to the Fifteenth General Assembly of the International Union of Geodesy and Geophysics (published in 1971 issues of *Transactions* of the American Geophysical Union).

Historical Background

The earth sciences have been shaped by a series of great controversies and a host of minor disputes. It has sometimes seemed that geologists enjoy the excitement of debate more than they enjoy getting together to define their terms in an effort to resolve a dispute. The great debate of this century is about continental drift, which is an old idea formulated originally to explain the striking parallelism between coastlines bordering the Atlantic Ocean. This parallelism was noted first by Alexander von Humboldt (1801). A book by Snider (1858) seems to have been the first of several works in the 1800s in which continental drift is explicit or implicit. Continental drift certainly is implicit in the classic works by Suess (1908, 1909) and Taylor

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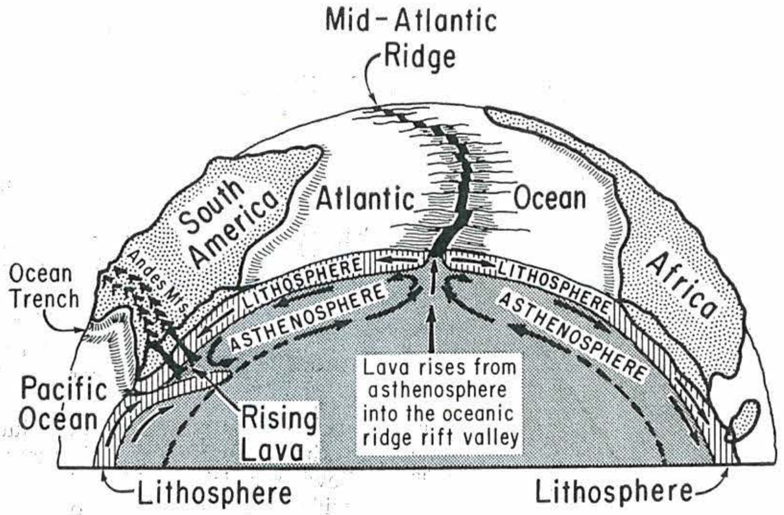

FIG. 1—Schematic representation of seafloor spreading and continental drift. Large plates of lithosphere containing continents migrate away from midoceanic ridges as if on a conveyor belt, and plates are carried into earth's interior along boundaries where plates collide.

(1910). However, Wegener (1912) generally gets the credit for originating modern concepts of drift. What Wegener really did was to promote the idea more fully and forcefully than anyone before him.

Wegener's 1912 paper apparently was not well received, and he went off to the Greenland ice cap on an expedition led by J. P. Koch. After spending the winter at a base in northeast Greenland, they trekked 700 mi (1,120 km) across the ice cap with a team of ponies. During the long winter night at lat. 77°N there was little to do but complete the chores necessary for subsistence, admire the stark beauty of the surroundings by moonlight, and cogitate. Wegener's cogitations bolstered his faith in the idea of continental drift, and he renewed his efforts after returning home and published a book (Wegener, 1915). The great debate was under way.

The topic was sufficiently novel and challenging that it became the subject of varied discussions. Advocates of Suess's (1908, 1909) Gondwanaland found the hypothesis particularly appealing, and Wegener's views quickly gained wide acceptance in the Southern Hemisphere. The arguments pro and con raged until the 1930s, but they waned after the first symposium on continental drift, held by The American Association of Petroleum Geologists in New York City in 1926. The papers from this symposium, published by the AAPG (van der Gracht *et al.*, 1928), in essence discredited continental drift. In most parts of the United States the ideas received little further attention, although interest remained high in many other parts of the world. A major problem was that the physicists could find no mechanism for propelling the continents, even though Holmes published a convection hypothesis in 1928 and then proposed convection as a continental-drift mechanism in 1931. His model was similar in many respects to recent schemes (see Fig. 1).

In 1930, Wegener was in Greenland again as leader of the German Inland Ice Expedition. A major objective was to determine the thickness of the ice cap by using a new technique now known as "explosion seismology." Wegener perished tragically on the ice cap at the age of 50. Although he did not live to see general acceptance of his hypothesis, when he died he was pioneering a technique which later gave it strong support. Seismic data from oceanic ridges, active mountain chains, and volcanic island arcs now provide persuasive evidence for the new global tectonics.

By the late 1930s, about all that could be said for continental drift had been said, not once but many times, and either one believed it or did not.

In the 1950s, interest was revived by exploration of the ocean floor and the development of paleomagnetic studies. In 1960, the late Harry H. Hess (1960, 1962) revived Holmes's (1931) model of mantle convection and introduced the hypothesis of seafloor spreading. Hess considered the idea so fanciful that he called it "geopoetry." In the mid-1960s, an increasing variety of evidence lending support to the hypothesis was reported, and a bandwagon atmosphere developed.

In January 1970, a full page in *Time* magazine explained how Hess's geopoetry had become geofact, and the heading declared "It's a revolution." At about the same time, the *Journal of Geophysical Research*—another respectable publication—also was telling us that continental drift was proved fact. However, in 1968 articles had appeared in the *Journal of Geophysical Research* referring to the theory of "plate tectonics." Plate tectonics, as depicted in Figure 1, incorporates seafloor spreading from the oceanic ridges and accounts for continental drift. Therefore, I begin here with a review of plate tectonics and proceed to show how the other concepts are related.

Plate Tectonics

Figure 1 shows the general global scheme. The outer shell of the earth, about 100 km thick, is composed of relatively cool, rigid rock called the "lithosphere." This overlies the "asthenosphere" which, being warmer and less rigid, is capable of slow convective motion in the solid state. Convecting material rises beneath the oceanic ridges and carries the lithosphere away laterally as if on a conveyor belt. The seafloor is thus spread apart, and the tensional gap is filled with new ocean crust generated by the injection and eruption of magma rising from the depths. Where convection cells converge, a slab of lithosphere is carried into the earth's interior in a subduction zone, where it is heated, partially melted, and eventually assimilated. These locations are sites of compression characterized by mountain ranges or volcanic island arcs and oceanic trenches. Figure 1 shows that the continents form part of the lithospheric layer; as the lithosphere moves, so the continents drift.

Plate tectonics is concerned with the relative movements and interactions of the plates of lithosphere shown in Figure 1, and with the consequences of these movements and interactions through time. It is thus concerned largely with the surface and crust of the earth, although the causes of plate movements are within the earth.

The surface features of the solid earth are shown in Figure 2. There is a primary distinction between two levels, the continental platforms and the floors of the oceanic basins. Included with the continents are the epeiric seas and the submerged continental shelves. The primary tectonic features are the oceanic ridges, the geologically young mountain ranges and volcanic island arcs, the oceanic trenches, and the major fracture zones that transect the oceanic ridges.

According to plate tectonics, the earth is covered by a small number (6 to 20) of large, stable lithospheric plates moving relative to each other and having boundaries delineated by belts of tectonic activity. Signals of activity include earthquakes and volcanism. The oceanic trenches and ridges are well correlated with world tectonic activity, and more accurate information becomes available each year. The remarkable concentration of earthquakes along narrow belts is apparent from the maps of Barazangi and Dorman (1969, 1970) showing world seismicity in a recent 8½-year period (January 1961 to September 1969). The earthquake belts are represented in Figure 3 by the heavy lines; these belts are considered to delineate the boundaries of the rigid aseismic plates that are about 100 km thick (Fig. 1) and as much as thousands of square kilometers in area. The bounding earthquake belts can be correlated in Figure 2 with active oceanic ridges, oceanic trenches or subduction zones, and strike-slip faults of the transform variety (Wilson, 1965).

Thus, according to the theory of plate tectonics, the apparent, natural division of the earth's surface into continents and ocean basins (Fig. 2) is a relatively insignificant feature of the surfaces of the thick lithospheric slabs. The slabs themselves, however, are remarkably thin in contrast to their surface areas.

Distribution of earthquakes locates the boundaries of lithospheric plates, and the depths of earthquake foci provide information about the extension of rigid plates into the earth's interior. Intermediate- and deep-focus earthquakes are considered to delineate subduction zones like that depicted beneath the Andes in Figure 1.

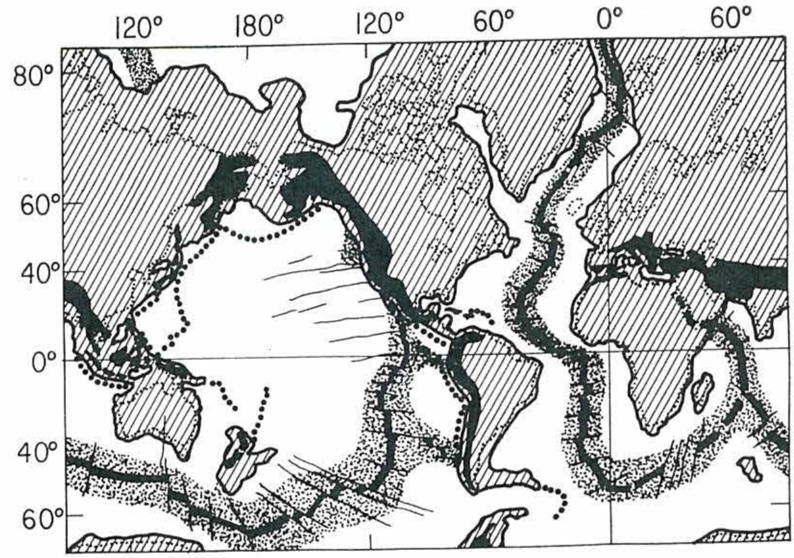

FIG. 2—Surface of solid earth. Stable continental platforms (diagonal shading) and stable ocean-basin floor (white) are traversed by active mountain belts (black) and submarine ridges (stipple). Rifted crest of midocean ridge system (thick black lines) is displaced into segments by fault zones (thin black lines). Heavy dotted lines show deep ocean trenches adjacent to volcanic island arcs or to continental margins. Earthquakes are associated with mountain belts, midocean ridges, oceanic trenches, and island arcs.

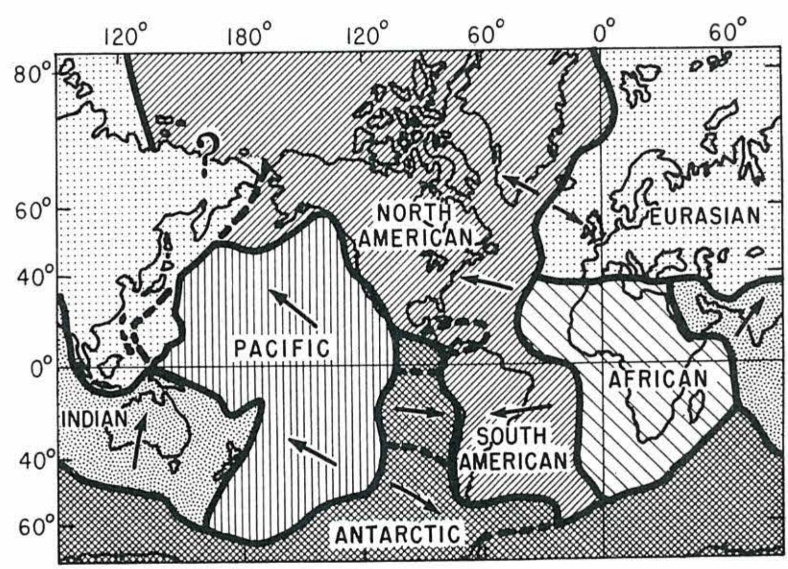

FIG. 3—Plate-tectonic model. Distribution of major rigid plates of lithosphere, relatively free of earthquakes, bordered by active earthquake belts. Compare plate boundaries with features in Figure 2. Line between continent and ocean is not significant with respect to lithospheric plates unless it coincides with active earthquake belt. Based on Isacks *et al.* (1968) and Morgan (1968).

The relative motions of adjacent lithospheric plates have been determined by the study of focal mechanisms of earthquakes. The average orientation of slip vectors for the earthquakes in a given earthquake belt defines the motion, and the arrows showing the directions of movement of some plates in Figure 3 are consistent with the idea of seafloor spreading from the oceanic ridges.

Recent seismic activity defines the present boundaries and relative motions of the lithospheric plates, but this activity does not indicate how long the movements have continued or whether the movements have remained continuous in direction and speed. The inferred existence of lithospheric slabs extending 700 km into the earth's interior implies that the process continued at least long enough to transport the lithosphere laterally through 700 km. Rates of movement must be known before times can be estimated, and to determine these rates one must study seafloor spreading.

Seafloor Spreading

The lithospheric plates move because the seafloor is spreading away from those belts of seismicity that follow the oceanic ridges and associated transform faults. I have already reviewed the convection-cell–conveyor-belt model in Figure 1. By analysis of the stages of seafloor spreading, geologic history can be traced backward in time.

The critical evidence for the model is based on the history of polarity reversals in the earth's magnetic field. These changes are imprinted on the newly generated lithosphere at the oceanic ridges. The process of imprinting has been compared with the imprinting on magnetic tape by a magnetic tape recorder. The concept was published first by Vine and Matthews (1963), but was developed independently by Morley in 1963 (see Morley and Larochelle, 1964).

Magnetic-Field Reversals and Geomagnetic Time Scale

The earth behaves as if it encloses a large magnet with a magnetic axis almost parallel with the earth's rotational axis. Figure 4A shows schematically the hypothetical dipole magnet and the distribution of lines of force around the earth at the present time. The present arrangement is, naturally, defined as "normal." Figure 4B shows the magnetic field reversed in comparison to Figure 4A, and this requires reversal of the hypothetical dipole magnet as well. What is the evidence that polarity reversal has ever occurred?

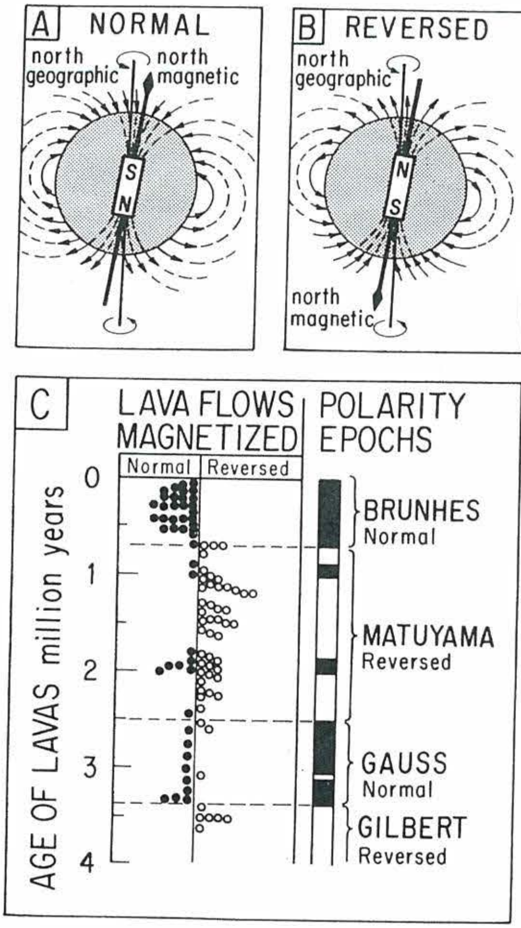

FIG. 4—Lines of force associated with earth's magnetic field: **A,** with normal polarity; **B,** with reversed polarity. **C** shows geomagnetic polarity-reversal time scale determined by directions of fossil magnetization of radiometrically dated lavas.

Lava becomes weakly magnetized as it cools, and the direction of magnetization preserves a fossil record of the direction of the earth's magnetic field at the time and place of solidification of the lava. Figure 4C shows the polarity-reversal time scale that has been established from paleomagnetic studies of rocks from vertical sequences of radiogenically dated lavas at the earth's surface. The lava flows range in age from the present to 4 m.y. (Cox *et al.*, 1964; Doell and Dalrymple, 1966; Cox, 1968). The magnetized directions of the lavas, which are from various parts of the world, show a pattern of alternating polarities termed "polarity epochs" and shorter intervals termed "polarity events." The error in the dating method becomes too large to extend this time scale backward beyond about 4 m.y. ago, because the error exceeds the total duration of many polarity events. However, using a similar approach and measuring the age and polarity of a wide range of rocks, McElhinney (1971) presented a reversal pattern through the whole of Phanerozoic time.

Magnetic Anomalies of Ocean Basins

The hypothesis of seafloor spreading became theory when the sequences of weak, linear magnetic anomalies which at the present time parallel the oceanic ridges were measured and correlated with the time scale for the earth's polarity reversals. Vine and Matthews (1963) proposed that the magnetic anomalies were caused by the magnetization of alternate strips of the ocean floor in opposite directions, and they explained the existence of such strips by correlating the anomalies with seafloor spreading and polarity reversals, as illustrated schematically in Figure 5; this is the "magnetic tape recorder" analogy.

If one assumes, quite arbitrarily, that seafloor spreading began at a ridge 3 m.y. ago, then eruptions of lava during successive polarity epochs before that time would have produced no directional magnetic properties in the oceanic crust, and no systematic magnetic-anomaly pattern would be expected. Figure 5A shows the effect produced during part of the Gauss normal epoch (Fig. 4C), between 3 and 2.75 m.y. ago, as the new crust *a-b* was generated from magma and spread laterally from the ridge crest. This rock was magnetized in the direction of the existing (normal) magnetic field, producing a positive magnetic anomaly along the ridge crest. The Matuyama reversed-polarity epoch began about 2.5 m.y. ago (Fig. 4C). Continued spreading for 0.25 m.y. produced the situation in Figure 5B, where the block of new crust *c-d* is shown to be magnetized in the direction opposite to that of the original block *a-b* in Figure 5A. The block *c-d* produces a positive anomaly above it, and the older crust, now separated into the two blocks *a-c* and *d-b*, produces negative anomalies in the earth's reversed magnetic field. In this way, the sequence of polarity reversals for the earth (Fig. 4C) is believed to become imprinted on the spreading oceanic crust. Figure 5C is a cross section of the sequence of magnetized strips resulting from the polarity reversals of the past 3 m.y. The alternating directions of magnetization of the strips produce the series of positive and negative anomalies, symmetrically disposed about the ridge crest. Each anomaly boundary in Figure 5C, when correlated with the appropriate reversal time in Figure 4C, gives the time taken for the oceanic crust to spread laterally to its present position from the ridge crest, where it was generated.

The magnetic anomalies parallel with the

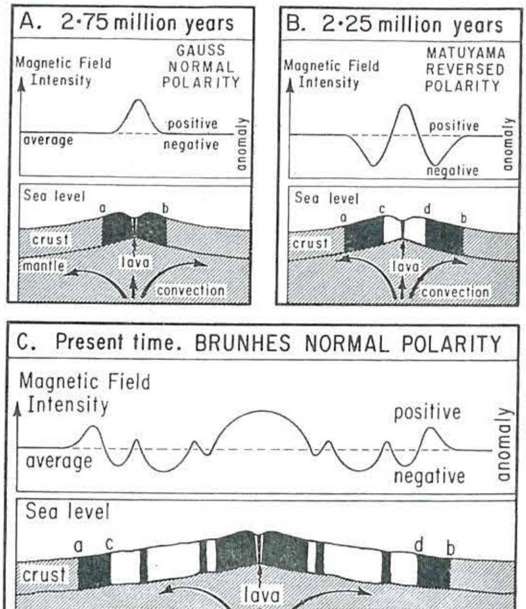

FIG. 5—Schematic representation of sequence of magnetization of new ocean floor generated at mid-ocean ridges as lithosphere is transported laterally away from ridge. Blocks of crust (with directions of magnetization alternating as reversals of magnetic field take place; see Fig. 4C) produce alternate positive and negative anomalies on earth's ambient magnetic field as measured at sea level.

Reykjanes Ridge, a part of the Mid-Atlantic Ridge southwest of Iceland, show good symmetry about the ridge, and the ratios of the widths of successive anomaly bands correlate closely with the successive polarity epochs and events. The publication of these results by Heirtzler *et al.* in 1966 was hailed as proof of seafloor spreading (Vine, 1966).

Average rates of spreading from various ridges as determined from magnetic-anomaly bands range from about 1 cm/year to more than 6 cm/year. Thus, the time scale in Figure 4C shows that the distances of the oldest dated rocks from ridge crests range from 40 km to more than 240 km. The pattern of recognizable linear magnetic anomalies extends much farther than this in many areas; therefore, if the assumption is made that spreading rates have remained constant, the spacing of the linear anomalies can be used to extrapolate the polarity-reversal time scale beyond the 4-m.y.-B.P. limit imposed by the dating method (Fig. 4C). In this way, the time scale has been extrapolated backward to about 80 m.y., as shown in Figure 6.

Easily identifiable anomalies have been numbered for reference purposes and for correlation from one profile to another. Each numbered anomaly is thus assigned a provisional age, as in Figure 6, and the distribution of anomalies in the ocean basins corresponds to the distribution of isochrons for the ocean-basin floor. The distribution of magnetic anomalies in many parts of the ocean is far less symmetrical and more complicated than for the Reykjanes Ridge. It is a long extrapolation from the accurately dated period of 4 m.y. ago (Fig. 4C) to the Cretaceous (80 m.y.; Fig. 6), and such extrapolation involves numerous assumptions. Unfortunately, the assumptions and the tenuous nature of the extrapolated geomagnetic time scale—although stated in earlier papers on this topic—tend to be overlooked in some of the subsequent publications and reviews.

Despite the provisional nature of the ages and the large amount of magnetic mapping still to be completed, the ability to contour the ocean basins with isochrons provides the prospect of unraveling the history of these basins, and the resultant movement of the continents, with a precision inconceivable during the debate about continental drift that occupied the first half of the century.

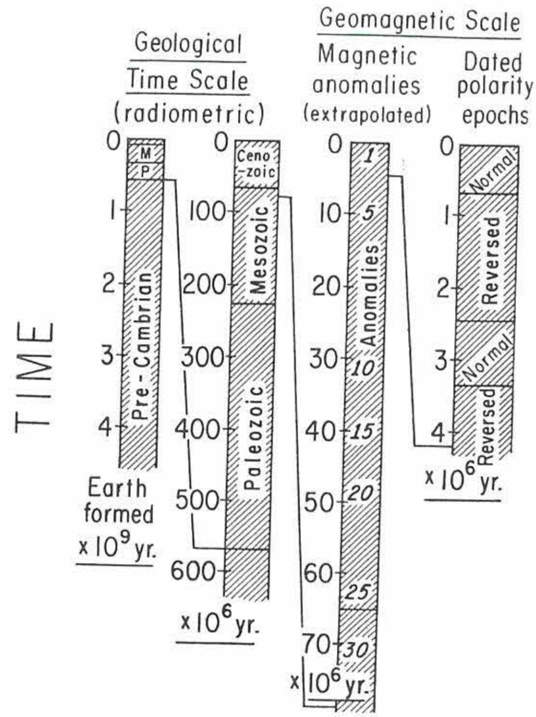

FIG. 6—Radiometric geologic time scale compared with geomagnetic time scale. See Figure 4C. Scale for each successive column is increased by factor of 10.

JOIDES Drilling Results

The *Glomar Challenger* (Fig. 7) began its cruises in 1968. Already, results of the JOIDES Deep Sea Drilling Project have been hailed widely as confirmation of the theory of seafloor spreading and plate tectonics. In the South Atlantic Ocean, the paleontologic ages of the deepest sediments above basaltic basement rocks agree very closely with the age of the basement according to the magnetic anomalies and the geomagnetic time scale back to almost 80 m.y. It has not been established, however, that the basalt which was penetrated is definitely basement rock. Deeper drilling may reveal more sedimentary rock below basaltic layers.

The need for prudence is indicated in a recent paper by Macdougall (1971). He dated basaltic basement in one of the drillholes of the western Atlantic Ocean basin as 16 m.y. old; it lay beneath fossiliferous Late Cretaceous sedimentary beds! Hopefully, the device illustrated in Figure 7 which permits removal of a drill core,

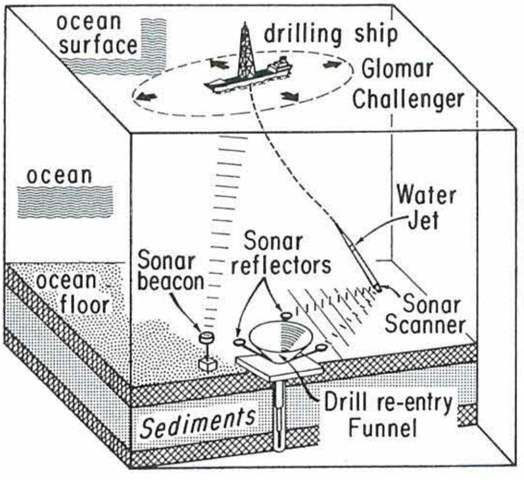

FIG. 7—Sketch of *Glomar Challenger* with drilling rig, dynamic positioning system, and reentry system on ocean floor.

replacement of a worn bit, and reentry of the drill string into the same borehole on the ocean floor will lead to more detailed studies of the nature and age of the basaltic rocks described as basement.

Subduction Zones

If large volumes of lithosphere are being generated at the oceanic ridges and the rigid plates are spreading away from the ridge crests, where is all the material going? If one assumes that the earth is not expanding, lithosphere must be removed at the same rate it is generated. The Pacific plate moving northwest from the East Pacific Rise (Figs. 2, 3) obviously must disappear in subduction zones extending beneath the oceanic trenches that festoon the northwest Pacific Ocean.

The accepted interpretation is that the lithospheric plate is continuous, in a tectonic sense, and that the lithospheric slab bends at the trenches and moves down beneath the island arcs (or marginal mountain range, as in Fig. 1). This interpretation presents mechanical problems. Lliboutry (1969) proposed one of several solutions that have been published. He postulated that the continuous oceanic plates are sheared into vertical fragments beneath the oceanic trenches, and that the contiguous fragments move down into the asthenosphere in such a way that the overall picture is one of an inclined plate dipping into the interior.

CONTINENTAL DRIFT

Figure 1 shows the South Atlantic Ocean increasing in width by seafloor spreading. The lithospheric plates are about 100 km thick, and the continents range in thickness from 35 to 70 km. They move with the plates like logs frozen into an ice floe; this is the common analogy drawn. Wegener's (1912, 1915) original concept of continents "sailing" through a sima (mafic) sea was discredited in the van der Gracht *et al.* (1928) symposium. In the new concept of plate tectonics, however, Wegener's mechanism need not be invoked, and thus one of the greatest obstacles to the continental-drift idea no longer exists.

Continental Fits

Therefore, continental drift is simply a result of seafloor spreading during the course of plate-tectonic activity. If the spreading process illustrated in Figure 1 were reversed at the same half-rate of 2 cm/year, then 4 cm of ocean floor would disappear each year, and in less than 150 m.y. the South Atlantic Ocean would be closed and the continents of Africa and South America would be in contact. A glance at the map of the Atlantic Ocean (Figs. 2, 3) makes it obvious to the drifter that the continents on either side of the Atlantic, and the Mid-Atlantic Ridge, were once joined. However, Dietz (1967, p. 73) presented a sketch showing how one does have to stretch the evidence a little to make the apparently obvious fit work.

Bullard *et al.* (1965) were tired of the repeated criticism by nondrifters that the continents did *not* fit across the Atlantic. Therefore, they put the computer to work and came up with an objective fit designed to satisfy everyone; and even if it does not satisfy everyone, it certainly seems to have satisfied the majority.

However, geometric fits are not really good evidence for or against drift, as Voisey (1958) and Lyustikh (1967) showed only too well. Therefore, it is logical to seek an independent line of evidence to determine whether continental drift has taken place. *Is* there an independent line of evidence? Fortunately, there is.

Paleomagnetism

The earth has a magnetic field (Fig. 4A) and, if it can be assumed that the approximate axial dipole field of today has predominated during the whole of earth history, then one can use some of the principles of paleomagnetism to see whether continents have drifted. If they have, it is possible to determine their "wandering" paths. The theory is based on the fact that a rock becomes magnetized in the direction of the magnetic field prevailing at the time the magnetic material in the rock was formed. From oriented rock specimens collected in the field, one may then determine the ancient paleolatitude and the distance from the magnetic pole of the rock when it was magnetized. If the magnetic axis of the past coincided with the rotational axis, then one has, from paleomagnetic measurements, a record of the locations in the past of the rotational axis. The whole collection and measurement process is one which requires great delicacy, care, and precision.

Studies of oriented rock specimens ranging in age from the present to 20 m.y. old show that the paleomagnetic pole has not moved much during these 20 m.y. relative to the rock locations. Statistically, in fact, the pole has not moved at all. There *is* a wide spread in plotted pole positions; that is to be expected in paleomagnetic studies. The spreads are so wide that elaborate statistical procedures must be applied to the results in order to determine an average pole position.

Rocks older than 20 m.y. show that the paleomagnetic pole—and by inference the rotational pole—has moved relative to the continents, or vice versa. In fact, the farther back in time one goes, the more divergent are the pole positions. Rocks measured from a single continent give a path of polar wandering through time, showing the position of the paleomagnetic pole relative to the position of the continent.

If continents have held the same relative positions with respect to one another through time, the polar-wandering paths of all continents should coincide. They do not. The polar-wandering paths for North America, Europe, Asia, Africa, India, South America, and Australia diverge from each other. Therefore, on the basis of these paths, one may conclude that the continents have moved with respect to each other. Some reasonably consistent pictures now seem to be emerging from attempts to reconstruct the relative positions of the continents at different times, extending back to more than 500 m.y. ago (Fig. 6).

Reconstruction of Pangaea by Dietz and Holden

Wegener had outlined the breakup and dispersal of the original supercontinent called "Pangaea." In 1970, Dietz and Holden positioned Pangaea for the first time in absolute coordinates on the earth's globe. Their guiding rationale for the reconstruction was the drift mechanism associated with plate tectonics and seafloor spreading (Figs. 1, 3, 5). Using these same guidelines, they prepared four maps illustrating the breakup and dispersion of the continents during the past 180 m.y. Absolute geographic coordinates were assigned for the continents, as well as for the active oceanic rift zones and the oceanic trenches, as the continents migrated to their present positions.

They also extrapolated present plate movements to predict the appearance of the world 50 m.y. from now. Among the anticipated changes are northward movement of Australia into contact with the Asian plate, easterly shift of India, the virtual closure of the Mediterranean Sea, and some significant changes in the geography of California. They estimated that in about 10 m.y. Los Angeles, on the Pacific plate, will be abreast of San Francisco, on the American plate (Fig. 3), and in about 60 m.y. Los Angeles will start sliding into the Aleutian Trench south of Alaska. The nice thing about such predictions is that it will take millions of years to prove or disprove them!

Causes of Plate Motions

Those who still feel somewhat dissatisfied about the evidence for lateral movements at the earth's surface might be happier if the causes of these movements were known—but the causes are *not* known. With this fact understood, we can speculate. One basis for speculation on the dynamics of the earth's interior is a study of the effects of surface movements. Studies of effects such as earthquakes may provide clues to the causes.

According to the theory, earthquakes result when plates collide at the margins. Most of the major earthquakes around the Pacific are attributed to the subduction of oceanic plates beneath island arcs or mountain ranges. For example, a disastrous earthquake in the Peruvian Andes in 1970 killed 50,000 people. It caused half a mountainside to move downward a distance of 4 km and laterally a distance of 15 km. Within a few minutes, this mass of earth, rocks, and melting ice, rushing at velocities on the order of 300 km/hour, buried the village of Yungay in the valley below, in places to a thickness of 15 m (Browning, 1973).

I have illustrated elsewhere (Wyllie, 1971a, p. 354) four mechanisms that have been considered. The first is a simple convection cell in the asthenosphere—the conveyer-belt model (Fig. 1). The second shows a passive plate being underridden by a cold downgoing plate; gabbro is converted by polymorphic transition to denser eclogite, and the slab sinks, pulling the plate behind it. The third shows a slight slope from the flanks of the ridges, and the oceanic lithosphere slides toward the continents under the action of gravity. In the fourth model the plates are being pushed; it has been suggested that a sort of magmatic head is built up beneath the ridges, and that the resulting stress pushes the plates to either side.

None of these models really works. Not one of the processes proposed can work to the exclusion of the others and, if a mechanism ever is worked out, it probably will involve all of these processes.

At the University of Chicago, where I teach and do research, mantle motions have attracted the attention of several experts in fluid dynamics. Experimentation and theoretical research with their familiar convective systems in water or air have not been directly applicable to material with the properties of the mantle, but the experts faced the challenge. Their conclusions to date are that there is no complete mathematical or dynamic theory of seafloor spreading, and they see little prospect of formulating one until more data are available. There seems to be some doubt as to whether the critical data ever can be obtained.

Discussion

This, then, is today's ruling theory and the status of its model. I think it is important to remember that many other models and many other hypotheses have been proposed. Yesterday's model is of historic interest only—although within it one may find the clue for the model of today. One must also remember, however, that today's model is tomorrow's history. Today's model of global tectonics looks far better than any previous hypotheses on the matter.

I think that we should work the theory of the new global tectonics for all it is worth—just as we should do with any theory or model, for it is through such intensive studies that we obtain large quantities of valuable information. We should reexamine the geologic data within this new conceptual framework, but we must not assume that we have arrived at the final solution—because geology just is not that simple. Wegmann (1963) wrote: "Commonly the motions, concepts, and hypotheses control the selection of facts recorded by the observers. They are nets retaining some features as useful, letting others pass as of no immediate interest. The history of geology shows that a conceptual development in one sector is generally followed by a harvest of observations, since many geologists can only see what they are asked to record by their conceptual outfit." What we have to do now is use the conceptual outfit but not be hampered by conceptual blinkers.

The ardent advocates of plate tectonics as a panacea for all problems in earth science are wont to say something like this. They say that certainly there are minor details which we cannot yet fit into the model; however, we can attribute these details which do not fit to a present lack of understanding rather than to any flaw in the new global scheme. They say to themselves that all will become clear in due course. Perhaps this is true. Nevertheless, we surely owe it to ourselves and to the ghostly authors of theories past to examine critically all evidence which appears to support the hypothesis, to consider carefully any evidence which does not fit the hypothesis, and to continue to seek alternate explanations for all of the evidence.

Of the following articles in this volume, some are strongly for the new global tectonics, some are strongly critical and present data which do not appear to fit, and others are neutral. One article presents a new interpretation of the linear magnetic anomalies of the ocean basins; I have noted that these anomalies have provided one of the strongest arguments in favor of the new global tectonics. Hopefully, the reader will find these papers stimulating and thought-provoking, and will strive to combat the ". . . natural coldness toward those [facts] that seem refractory" to his preferred theory (Chamberlin, 1890).

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Memoir 23

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